NASA CR-176,724

NASA-CR-176724
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DISCUSSION OF FLIGHT EXPERIMENTS WITH AN ENTRY RESEARCH VEHICLE

(NASA-CR-176724) DISCUSSION OF FLIGHT EXPERIMENTS WITH AN ENTRY RESEARCH VEHICLE (Vanderbilt Univ.) 40 p HC A03/MF A01 CSCL 22A
N86-23628
Unclas
G3/18 15757

J. Leith Potter

NASA Research Grant NAG-1-549

Semiannual Status Report No. 1

June 30, 1985

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Period Covered: December 1, 1984 - June 30, 1985

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SUMMARY

This is a report of a preliminary study of benefits to be derived and the data to be sought by Entry Research Vehicle (ERV) flight experiments. The focus of interest is maneuvering flight at altitudes above 50 km and velocities of 5-8 km/s. Laboratory simulation of this flow regime is inadequate, and it is recognized that nothing short of flight test data will resolve issues that now arise when designs of advanced space shuttles and orbit transfer vehicles are discussed. Although deficiencies in our ability to accurately predict heating and forces under low-density, hypervelocity conditions are apparent, it is not clear how successful the needed flight experiments may be when conducted under the limitations of current measurement capabilities. Therefore, the problem involves not only identification of specific measurements, but also applicable apparatus and techniques. The first of these tasks is the main concern of this study.

The needed data are discussed and measurement techniques that appear to be most applicable are identified. In the majority of these cases, further study is believed to be necessary before confident assessments can be made. However, the probabilities for beneficial flight-test results are high enough to justify serious effort toward defining the experimental

apparatus, techniques, and probable outcomes. Measurements discussed include the following:

(1) Shock layer or boundary layer profiles of velocity, temperature, species mass fractions, and other gas properties associated with aerodynamic heating,

(2) Surface energy transfer process at catalytic walls,

(3) Nonequilibrium flow processes and pressure distribution,

(4) Separated, vortical leeside flow of nonequilibrium fluid,

(5) Boundary layer transition on highly swept configurations, and

(6) Shock and surface slip and gas/surface interaction.

It is concluded that, at the 1985 state of the art, the desired measurements are feasible in portions of entry vehicle flight envelopes, but that the desired data accuracy or coverage may not be achieved under the more unfavorable conditions. Further study should focus on evolving measurement techniques, installation requirements, and on the identification of the portions of the flights where successful results seem probable.

INTRODUCTION

The aerodynamic forces and heating on hypervelocity maneuvering vehicles at altitudes above roughly 50 km are the subjects discussed. It has been proposed that the opportunity afforded by STS operations be utilized to gain valuable new information on aerothermodynamic phenomena in the transitional gas dynamic regime. Information thus acquired would lead directly to improved aerodynamic analysis of advanced reentry vehicles. An equal opportunity is not available through the utilization of wind tunnels or other laboratory facilities. The Entry Research Vehicle (ERV) Technology Plan under consideration by NASA has this goal. Aeroassisted and Aeromaneuvering Orbital Transfer Vehicles and other future programs would be supported. Further to that general goal, this report briefly reviews aerothermal issues of current concern, suggests experiments aimed at their elucidation, and comments on possible experimental approaches. The objective is identification of flight experiments that will yield data contributing to more efficient, higher performance, yet safe designs. In view of the technical difficulties and costs of flight experiments, evaluation of the feasibility and value of proposed measurements is particularly critical.

In the short time during which this study has been pursued, attention has been focused on discrepancies between predicted STS

orbiter aerodynamics during reentry and actual inflight measurements. This approach has revealed issues that need to be resolved before winged vehicles with expanded operating envelopes are designed. An early part of the work has been described in a paper which was presented at the AIAA 20th Thermophysics Conference, June 1985.[1]

To establish the background of this discussion of flight experiments, it is first necessary to define the general flight regime. This is done by Figs. 1 and 2, wherein both velocity-altitude and Reynolds number-Mach number coordinates are shown. The first figure outlines areas of operation proposed for STS, AOTV, and the Entry Research Vehicle (ERV). Only the envelope for the latter is shown in Fig. 2 because it is the focus of this study.

Even though the flight envelopes may encompass lower altitudes and velocities, it is only the higher ranges of both variables that are of concern here. Rather arbitrarily, we choose 50 km altitude and 5 km/s as lower bounds. That is because laboratory simulation of that area is deficient and flight experiments are necessary to answer questions about the gas dynamic phenomena that arise there. It is there that data from STS flights show the greater discrepancies with predicted results. Therefore, attention is directed to low-density hypervelocity conditions which are abbreviated LDH hereafter.

At the present time, insufficient understanding of some basic phenomena prevents the accurate prediction of forces and

heating on bodies in LDH flow. Among these are gas-surface interaction, catalytic-wall effects, slip effects, and nonequilibrium thermo-chemical-kinetic flow processes. The modeling of these phenomena remains highly uncertain because of difficulties in extracting the needed information from reentry flights, the limited scope of previous flight data, and the unsatisfactory simulation possible in available research laboratories. There are numerous questions that need to be answered if performance of existing vehicles or designs of new vehicles operating in LDH flow are to be more satisfactorily analyzed.

Wind tunnel investigations of the foregoing phenomena have given ample evidence of their existence and importance. However, it is recognized that no available wind tunnel enables experiments under conditions close enough to hypervelocity space flight to make the test results directly applicable when gas-surface interaction, slip, and/or nonequilibrium thermo-chemical-kinetic processes are factors.

As the first step in determining what ERV flight experiments would be most beneficial, results of aerodynamic force and heating measurements made during initial STS flights have been examined. When these data substantially disagree with predictive methods, it is inferred that the analytic methods are not reliable enough for the design of efficient, advanced vehicles with expanded operating envelopes. Possible causes of the deficiencies in predictive methods for the LDH flow regime are

reviewed, and approaches for flight experiments are considered in the following sections.

DISCUSSION

Aerodynamic Heating

This is a topic of primary concern in the present context. The approximate boundaries in Fig. 3 show that real gas thermo-chemical-kinetics, with the accompanying complications of nonequilibrium processes and surface catalytic reactions are encountered at the altitudes and velocities of interest. The boundaries in Fig. 3 are approximate because equilibrium processes and Rankine-Hugoniot normal shock waves are assumed. We must ask how well heating rates are predicted by methods now in use.

At present, STS data create some confusion. Zoby has shown that calculations based on equilibrium air processes agree rather well with STS-1 data for altitudes, $h < 53$ km.[2] However, agreement was obtained for STS-2 only for $x/L > 0.4$ at $h > 67$ km.[3] Below 67 km, STS-2 data agreed with equilibrium calculations all along the windward ray. Thompson[4] has obtained good agreement of STS-3 windward heating with perfect gas calculations for $h < 52$ km and agreement with equilibrium results at $60 < h < 70$ km. The troubling feature of this is that nonequilibrium air processes would be expected over much of the vehicle at $h > 50$ km, yet calculations accounting for nonequilibrium do not match STS-2 data in a number of cases.[3,5]

Generally poor agreement of STS-2 and -3 leeward heating data and wind tunnel data has been demonstrated at the reentry angle of attack, ~ 40 deg.[6]

It must be borne in mind that the ancmaloties just described may indicate more than problems with thermochemical-kinetic flow field processes; the basic computational process and uncertain degrees of catalytic wall effects also may share some blame. Wind tunnels that adequately simulate these phenomena are not available, and both model size and complexity are severely limited in aeroballistic ranges or tracks, so no resolution is to be forthcoming from laboratory experiments.

Zoby, et al.[7] recently have taken the approach of selecting values for temperature-dependent surface reaction rate coefficients of oxygen to force agreement with STS heating and wall temperatures in the range, $71 < h < 78$ km, when calculations are performed using their viscous shock layer program. It may be noted in Fig. 3 that oxygen is fully dissociated at STS orbiter speeds (6-7 km/s in the 70-80 km altitude range), while nitrogen is only partly dissociated. However, nitrogen dissociation energy is roughly double that for oxygen. That leaves the issue open as to whether the adjustment of surface reaction rates for oxygen alone is sufficient to correct all shortcomings in the analytical prediction. It may also be noted that viscous shock layer solutions do not appear to be valid for the STS configuration under conditions corresponding to $h > 100$ km.

Complications and uncertainty arise under hypervelocity

reentry conditions because different temperatures may characterize the different energy modes, such as translation, rotation, or vibration, and there is uncertainty about interrelations and rates of species formation and recombination. When the wall is not fully catalytic, the surface reaction or energy transfer process is an important factor. Both thermal and concentration diffusion are factors at temperatures over roughly 10,000 K. High temperature ionization reactions are not well understood, and considerable doubt exists for the flow regimes where nonequilibrium ionization is encountered. This problem affects the AOTV's more than the STS or ERV because of the higher velocities and shock layer temperatures of the AOTV type of operation.

Various simplified gas models are used when solutions for heat transfer rates are given and, not surprising, the results often are significantly different. Examples may be found in references 2-7 and the earlier publications referenced therein. Sometimes the real air in the shock layer is assumed to be a molecule-atom or binary mixture. Further advanced heating analyses take into account more than two species, e.g., reacting, thermally perfect O, O_2, N, N_2, and NO for SST and ERV conditions. For AOTV conditions the species considered might be O, O_2, N, N_2, NO, N^+, O^+, N_2^+, e^-.

The total heat transfer to a surface is determined by the thermal conductivity of the adjacent gas, temperature gradient normal to the surface, enthalpy of each species present,

concentration gradient of each species normal to the surface, velocity gradient normal to the surface, and local properties of the gas mixture and species, such as velocity, density, viscosity, diffusion coefficient, thermal conductivity, and the Lewis, Reynolds and Prandtl numbers. Various combinations of these parameters are possible when an equation for heat transfer rate is written. An example of such an equation is the following, cf. Ref. 5,

$$\dot{q} = \epsilon^2\left[K(\partial T/\partial y) + \mu(Le/Pr)\sum_{i=1}^{N} h_i(\partial C_i/\partial y) + \mu u(\partial u/\partial y)\right]$$

where $\dot{q}$ = heat transfer rate/$(\rho_\infty U_\infty^3)$

$\epsilon^2 = \mu_{ref}/(\rho_\infty U_\infty Rn)$

μ_{ref} = viscosity based on reference temperature, U_∞^2/Cp_∞

ρ_∞ = freestream density

U_∞ = freestream velocity

Rn = nose radius of curvature

K = thermal conductivity of mixture/$\mu_{ref}\, Cp_\infty$

T = temperature/T_{ref}

y = distance normal to surface/Rn

μ = viscosity of mixture/μ_{ref}

Le = Lewis number

Pr = Prandtl number

h_i = enthalpy of species i/U_∞^2

C_i = mass fraction of species i $= \rho_i/\rho$

u = local velocity tangent to surface/U_∞

Derivatives evaluated at surface.

If the data just listed were measured, with corresponding heat transfer rate, surface temperature and pressure, and edge-of-boundary layer flow conditions, a unique opportunity to assess gas dynamic and heat transfer calculations would be presented.

Such measurements, if possible, should be made where relatively simple flow exists, i.e., no separation, no crossflow, no ablation, and no other complexities that could obscure the basic thermo-chemical-kinetic effects on flow and heat transfer. It is also desirable for these measurements to be accompanied by measurements of freestream density, velocity, (some) constituents, and vehicle attitude.

At present, it is not clear if all of the above measurements are feasible or if all of the data would be reliable. One is reminded of Kant's thought, "What are things in themselves like, uncontaminated by the conditions of our knowing them?"

A review of the possibilities of these types of measurements is reported in Ref. 8, and other discussions are presented in Refs. 9-11. Table 1 gives a summary of measurement techniques that seem most applicable and feasible, although it is emphasized that further study of this subject is needed. Attempted measurements which involve just as much uncertainty in data processing as there is in the physical quantities being investigated will

not be rewarding. Inasmuch as all of the measurements listed in Table 1 would require some degree of interpretation in addition to the actual data recording, it would be desirable to obtain the same results, where possible, by independent means. In Table 1, N represents number density and T_t, T_r, and T_v are translational, rotational, and vibrational temperatures, respectively.

It is observed that analytical solutions predict that the mass fractions of some species in a dissociated, nonequilibrium boundary layer may vary by several orders of magnitude within the boundary layer thickness, c.f Ref. 26. The effect of shock and wall slip at the higher altitudes ($h \geq 95$ km) can produce a doubling of the atomic oxygen and even greater percentage enhancement of atomic nitrogen mass fraction according to Ref.5. These high gradients, with or without slip phenomena at or near the body and shock wave, will make measurements along surface normal directions spatially sensitive. It seems likely that profiles of boundary layer or shock layer quantities, for the near future, will not be measured with the accuracy necessary to define all terms in heat transfer calculations. However, experimental data on species mass fractions present at well defined locations would help to improve nonequilibrium real gas analyses even if the data were not in the form of complete profiles for all constituents. Such data would also improve estimates of mixture properties.

Other Aerodynamic Issues

Increased knowledge of nonequilibrium gas processes would also improve an important part of flow field calculation. The three major areas where benefits of flight experiments could be significant are (1) effects of non-equilibrium processes on pressure distributions, (2) leeside separation and vortical flow of nonequilibrium air at high Mach numbers and low Reynolds numbers, (3) boundary-layer transition, and (4) rarefied-flow aerodynamics with strong shock-boundary layer interaction, slip, and gas/surface interaction. All of these represent relatively unexplored problems in the context of flight tests under LDH conditions. As noted previously, wind tunnels and other laboratory facilities do not enable satisfactory investigation of all aspects of these problems. To a large extent, what can be done in that regard has already been done. The main advances in LDH wind tunnel technology during the past 20 years are represented by flow diagnostics and computerized data flow diagnostics and computerized data handling systems. Basic simulation capabilities have not changed. However, a state-of-the-art LDH tunnel of adequate size could fill a useful role by enabling tests under perfect-gas conditions. This would provide baseline data for extrapolation to real-gas free-flight conditions by analytical methods. The listed areas for study are discussed below.

Nonequilibrium flow. The difficulty of measuring profiles of gas properties in flight already has been discussed. Perhaps the best that should be anticipated is identification of several species and their approximate mass fractions. That, along with measured wall pressures and freestream conditions would give the information necessary for checking calculated real-gas results. Expanding flows downstream of strongly shocked regions will display the more pronounced effects. Therefore, those are good places to look for real-gas and nonequilibrium evidence. An example of a calculated result is shown in Fig.4. The trouble in many of the problems discussed is the possibility of arriving at nearly the same computed result by different routes. If flight data are to improve the computations, there will have to be enough intermediate check points provided by the data to assure that the correct route is taken to the final heat transfer or pressure coefficient.

Leeside flow. The extensive flow probing necessary to map leeside flow fields does not seem feasible for flight experiments. Information may be gained from lee surface measurements, and flow visualization by electron beam "painting" could be feasible under some conditions. Combination of an electron beam and photography has produced excellent flow field pictures where large density changes occurred in low-density wind tunnels, but it will be necessary to review the requirements for use in a flight experiment. It may be feasible to get photographs of shock waves,

boundary layer-shock interaction zones, vortices, and other regions where sufficiently large density gradients exist. This photographic coverage would be helpful in analyzing leeside separated flow which, for example, influences lift, lift/drag ratio, and pitching moment. There is no way to prove it, but a possibility exists that the unexpectedly higher pitching moment experienced by the STS orbiter was caused by leeside flow being different from that in the wind tunnel. The combination of high Mach number and large departure from perfect-gas conditions has not been studied in connection with separated, vortical flows.

Boundary-layer transition. It has been noted that transition location on STS orbiters was not predicted with satisfactory accuracy.[3] However, newer analysis of the STS data in the light of results obtained for swept cylinders in low-speed flow suggests that leading-edge or attachment line contamination by surface roughness is controlling transition on STS orbiters.[27] Flight data for confirmation of this would be very useful. Surface heat transfer rates for locations on and off of the vehicle centerline would probably resolve this issue. Poll's analysis would guide the placement of the transducers. From these data, it would be possible to evaluate trade-off between leading-edge surface smoothness and heat protection requirements downstream.

Rarefied-flow phenomena. Slip and gas/surface interaction are the principal topics to consider here. These are unknowns that

inhibit analytical predictions of heating and forces under higher altitude, hypersonic conditions.

At the interface of rarefied gas and solid surface the no-slip condition of continuum boundary layer theory is not valid. As indicated in Fig. 5, the slip velocity characterizes a layer of the gas adjacent to but slightly off the solid surface. By a simple approach for monatomic gases, it can be shown that the slip or interface velocity, u_s, is (cf. Schaaf and Chambre[28])

$$u_s = (2-\sigma)(\lambda/\sigma)\,\partial u/\partial y$$

The same source also gives results credited to Kennard, namely

$$u_s = (2-\sigma)(\lambda/\sigma)\,\partial u/\partial y + 3\mu/(4\rho T)\,(\partial T/\partial s)_w$$

and

$$T_s - T_w = [(2-\alpha)/\alpha][2\gamma/(\gamma+1)](\lambda/P_r)(\partial T/\partial y)_w,$$

where

σ = the fraction of diffusely reflected molecules,

α = the thermal accommodation coefficient,

P_r = Prandtl number,

λ = mean free path,

γ = ratio of specific heats,

Subscript w indicates conditions of the wall,

Subscript s indicates conditions in the gas adjacent to the wall, and s,y = coordinates along and normal to the wall, respectively (see Fig. 5)

Kogan[29] has reviewed more recent analyses. With the slip conditions in the form

$$u_s = A(\mu/\rho)\frac{2}{RT}(\partial u/\partial y) + 2B(\mu/\rho)\,\partial \ln T/\partial x$$

and

$$T_s - T_w = \left[C\lambda/(\rho R)\right]\sqrt{\frac{\pi}{8RT}}\;\partial T/\partial y$$

he summarizes the work of numerous investigators. Rather than present all of these results individually, we disregard differences in basic approach and simply note that the reported values of A vary from 1.012 to 1.103, B varies from 0.3292 to 0.4456, and C varies from 0.8155 to 1.173.

It is evident that some uncertainty in calculations of slip effects exists, and this carries over into predictions of heat transfer rates, skin friction, and other quantities. The velocity and temperature profile measurements that would improve ability to analyze slip conditions are among the ones already discussed in the heat transfer section. Added to these are α, σ and mean free path, λ. The latter may be expressed in the familiar form for elastic or hard-sphere molecules, i.e.,

$$\lambda_{hs} = 1.28\;/(\rho\sqrt{RT}),$$

where R = specific gas constant.

It is well known that, λ as defined above, is more appropriate for molecules at very high temperatures where $\mu \propto \sqrt{T}$. Bird [30] has shown how a more realist "variable-hard-sphere" molecular model,

appropriate for gases where $\mu \propto T^{\omega}$, leads to

$$\lambda_{VHS}/\lambda_{HS} = (7-2\omega)\ (5-2\omega)/24.$$

In any case, data of the type desired for improved heating rate analysis, would also improve understanding of slip phenomena. Measurements of σ and α are discussed in the next section.

Gas-Surface Interaction. In regard to altitudes above roughly 100 km, this subject is recognized as a dominant issue in discussions among gas dynamicists who have worked on problems of rarefied flow. The transfer of momentum or energy between gas and solid is influenced by the characteristics of both approaching and reemitted molecules. Molecules, with a distribution of velocities approach the surface, molecules are reemitted from the surface with a different velocity distribution, and a variety of classes of collisions occur. For example, collisions occur between freestream and reemitted molecules, and reemitted molecules are deflected back for a second impact on the surface, etc. Under conditions of extreme rarefaction, in the free-molecular flow regime, it is reasonable to focus on the impact of freestream molecules on the surface and the subsequent remission that occurs. Even that simplification does not eliminate the uncertainty concerning the nature of the reflection in a specific engineering application.

The gross features of gas molecular impact on a solid surface are indicated in Fig. 6. Diffuse reflection is represented by the spherical distribution, much as if the molecules were trapped just below the surface and then effused with no memory of their incident velocity direction.

Laboratory data, as presented in Hurlbut's[31] review paper show that the density distributions of the reflected molecules generally form lobes with their axes roughly in the direction of the specular reflection. Increasing the temperature of the incident beam causes the reflected maxima to shift toward the surface, and the distribution lobe maxima shift away from the surface as surface temperature increases. Narrowing of the density distribution lobes occurs as gas temperature increases. Again, increasing surface temperature causes an opposite effect, namely, increasing width of the lobal pattern.

When analyzing energy exchange between the incoming gas and the surface, a thermal accommodation coefficient is defined as

$$\alpha = (dE_i - dE_r)/(dE_i - dE_w),$$

where E_i = energy flux incident on wall,

E_r = energy flux reemited from wall,

and E_w = energy flux that would be reemitted if molecules were reemitted with a Maxwellian distribution corresponding to wall temperature.

For perfect accommodation, $\alpha = 1$. When $\alpha = 0$, there is no energy exchange. This concept implies that all energies associated with the molecular degrees of freedom are accommodated

to the same degree. That may not be the case for all energy components, but is is a common assumption. Numerous measurements of for various surfaces and gases have been made, but the wide range of data serves to emphasize the critical influences of factors involved.

To gain some additional flexibility, two coefficients are used to specify the tangential and normal force components separately in the analysis of momentum transfer:

$$\tau' = (\tau_i - \tau_r)/(\tau_i - \tau_w)$$

and

$$\sigma' = (P_i - P_r)/(P_i - P_w),$$

where τ_i = tangential momentum flux incident,

τ_r = tangential momentum flux reflected,

τ_w = tangential momentum flux reflected with a Maxwellian distribution at wall temperature (=0),

P = normal momentum flux and the subscripts have the same meanings as for the τ's.

In the case of specular reflection with no energy exchange,

$$\alpha = \tau' = \sigma' = 0,$$

and for diffuse reflection with full accommodation,

$$\alpha = \tau' = \sigma' = 1.$$

These equations represent the traditional approach to momentum transfer. However, it has been clear for a long time that this approach does not adequately model the gas-surface interaction revealed by modern experimental techniques.

It is indicated by experimental data that the accommodation coefficients may depend on surface cleanliness, roughness, temperature, and also gas temperature, velocity, species, and incidence angle. At this time, a data bank where one may obtain the required information for the surface and gas conditions of typical design problems does not exist. Nocilla[32] has pointed the way to a better model for the gas-surface interaction and Hurlbut and Sherman[33] have adapted Nocilla's model for predicting forces on bodies in free-molecular flow. Nevertheless, the exploitation of this more recent interaction model is inhibited by the variability of conditions met in practice and uncertainty about the corresponding interaction data.

The type of flight experiment that could be planned for increasing knowledge of gas/surface interaction would make use of the high altitude (>100 km) environment and high speed of the vehicle to provide a ready-made molecular beam. This concept is illustrated in Fig. 7. The sample surfaces would be exposed to the beam, at different orientations, and two components of force

on the sample would be measured, thereby providing tangential and normal momentum accommodation data. Freestream data would be collected by impact pressure probe and mass spectrometer. The same approach could be used to obtain thermal accommodation data if temperatures instead of forces were measured. Consideration would have to be given to shielding of the apparatus from interference emanating from the ERV, and the necessity to deploy the apparatus on an arm would impose a lower altitude limit on the operation. However, that would not diminish the value of the data.

One may ask why free-molecular flow is of practical importance in view of the low forces and heating rates under that condition, but it should be noted that the free-molecular values of aerodynamic force coefficients provide anchor points for bridging formulas that are often used for predicting transitional-flow aerodynamics. Furthermore, total heat loads and retarding forces at orbital conditions are the results of integrations over long times, so that even small additive quantities are of interest.

A flight experiment of this general type has been suggested in Ref. 34, where the general experimental arrangement for determining accommodation coefficients is attributed to H. Legge, of the DFVLR, and E. Steinheil, of Dornier, in West Germany.

CONCLUDING REMARKS

At the current (1985) level of capability, it does not appear that all of the detailed gas flow and property data needed for complete and conclusive checking of calculation methods can be measured in flight with the required accuracy. This does not mean that significant benefits would not be gained from feasible measurements and partial data. This status report presents a series of suggested measurements, with only cursory attention to techniques and probable accuracy. The latter topics obviously need more study. Recognizing that advanced entry vehicles will operate at a wider variety of attitudes compared to the STS orbiter, and that higher efficiency is a requirement, the value of information leading to more accurate aerodynamic analyses is motivation enough to pursue this study. See, for example, discussion of the trade-offs of airframe weight, propellant weight, and payload in Freeman, et al.[35] and Walberg.[36] Also to be considered are the benefits accruing to future entry vehicle designs from the experimental data on structural heating and loads, and benefits to lower-speed aeronautics research from the development of measurement systems which will also be applicable in that field.

It is recommended that the most recent advances in physical/chemical gas dynamic measurement techniques be reviewed

and evaluated in light of the needs outlined herein. The opinions of others regarding needed measurements as well as experimental approaches also should be sought.

The desired measurements seem feasible in portions of entry vehicle flight envelopes, but the desired data accuracy or coverage may not be achieved under the more unfavorable conditions. Thus, in addition to further attention to evolving measurement techniques and installation requirements, there is need to identify the portions of the flights where successful results seem probable.

REFERENCES

1. Potter, J. Leith. "Transitional, Hypervelocity Aerodynamic Simulation and Scaling in Light of Recent Flight Data," AIAA Paper 85-1028, AIAA 20th Thermophysics Conference, Williamsburg, VA, June 19-21, 1985.

2. Zoby, E. Vincent, "Comparisons of STS-1 Experimental and Predicted Heating Rates", Journal of Spacecraft and Rockets, Vol. 20, May-June, 1983, pp. 214-218.

3. Zoby, E. Vincent, "Analysis of STS-2 Experimental Heating Rates and Transition Data", Journal of Spacecraft and Rockets, Vol. 20, May-June, 1983, pp. 232-237.

4. Thompson, Richard A., "Three-Dimensional Viscous Shock-Layer Applications for the Space Shuttle Orbiter", AIAA Paper 85-0246, AIAA 23rd Aerospace Sciences Meeting, Jan. 1985.

5. Shinn, Judy L., and Simmonds, Ann L., "Comparison of Viscous Shock-Layer Heating Analysis with Shuttle Flight Data in Slip Flow Regime", AIAA Paper 84-0226, AIAA 22nd Aerospace Sciences Meeting, Reno, Jan. 1984.

6. Throckmorton, D. A. and Zoby, E. V., "Orbiter Entry Leeside Heat-Transfer Data Analysis", Journal of Spacecraft and Rockets, Vol. 20, Nov. - Dec. 1983, pp. 524-530.

7. Zoby, E. V., Gupta, R.N., and Simmonds, A.L. "Temperature-Dependent Reaction-Rate Expression for Oxygen Recombination at Shuttle Entry Conditions," AIAA Paper 84-0224, AIAA 22nd Aerospace Sciences Meeting, Jan. 9-12, 1984.

8. Miles, R. B., Santavicca, D. A., and Zimmerman, M. "Evaluation of Non-Intrusive Flow Measurement Techniques for a Re-Entry Flight Experiment," NASA CR-172142, Nov. 1983.

9. Wood, G. M., Lewis, B. W., Upchurch, B. T., Nowak, R. J., Eide, D. G., and Paulin, P. A. "Developing Mass Spectrometric Techniques for Boundary Layer Measurements in Hypersonic High Enthalpy Test Facilities," IEEE Int. Congress on Instrumentation for Aerospace Simulation Facilities," St. Louis, France, Sept. 1983.

10. Brown, K. G., Fishel, C., Wood, G. M., and Lewis, B. W. "Characterization of a Multichannel Plate as a Possible Inlet System for a Mass Spectrometer," ACS Annual Meeting, Philadelphia, Sept. 1984.

11. Wood, Jr., G. M., Hoppe, J., Eide, D. G., and Lewis, B. W. "Candidate Techniques for Non-Intrusive Measurement of Flight Boundary Layer Properties," AIAA Paper 85-0970, AIAA 20th Thermophysics Conference, Williamsburg, VA, June 19-21,1985.

12. Muntz, E. P. "The Electron Beam Fluorescence Technique," AGARDograph 132, 1969.

13. Muntz, E. P. In Methods of Experimental Physics, 18B R. J. Emrich, ed. Academic Press, NY, 1981.

14. Coe, D. Robben, F., and Talbot, L. In Rarefied Gas Dynamics, R. Campargue, ed., C.E.A., Paris, 1978.

15. Cattolica, [illegible] "OH Rotational Temperature from Two Line Laser Excited Fluorescence" Applied Optics, 20, 1156-1166, 1981.

16. Bischel, W. K., Perry, B. E., and Crosley, D. R. "Detection of Fluorescence from O and N Atoms Induced by Two-Photon Absorption," Applied Optics, 21, 1419-1429, 1982.

17. McKenzie, R. L., and Gross, K. P. "Two-Photon Excitation of Nitric Oxide Fluorescence as a Temperature Indicator in Unsteady Gasdynamic Processes," Applied Optics, 20, 2153-2165, 1981.

18. Dyer, M. T., "Rayleigh Scattering Measurements of Time Resolved Concentration in a Turbulent Propane Jet," AIAA Journal, 17, Aug. 1979.

19. Schefer, R. W., Dibble, R. W., and Driscoll, S. F., "Mass Fluxes $\rho' u'$ and $\rho' v'$ Measured in a Turbulent Nonpremixed Flame," Paper WSS/CI 82-35, Spring Meeting of the Western States Section of the Combustion Institute, 1982.

20. Blanchard, R. C., Duckett, R. J., and Hinson, E. W. "The Shuttle Upper Atmosphere Mass Spectrometer Experiment," Jour. of Spacecraft and Rockets, 21, Mar. - April 1984, pp. 202-208.

21. Potter, J. Leith, Kinslow, M., and Boylan, D. E. In Rarefied Gas Dynamics, Vol. 2, (J. H. deLeeuw, Ed.) 4th Symposium, Academic Press, NY, 1965.

22. Potter, J. Leith and Bailey, A. B., "Pressures in the Stagnation Regions of Blunt Bodies in Rarefied Flow," AIAA Jour., 2, April 1964, pp. 743-745.

23. Kinslow, Max, and Potter, J. L., In Rarefied Gas Dynamics, (D. Dini, Ed.) 7th Symposium, Edizioni Tecnico-Scientifiche, Pisa, 1971.

24. Lewis, J. H. and Smith, J. A., In Rarefied Gas Dynamics, (D. Dini, Ed.) 7th Symposium, Edizioni Tecnico-Scientifiche, Pisa, 1971.

25. Guy, R. W. and Winebarger, R. M., "Effect of Orifice Size and Heat Transfer Rate on Measured Static Pressure in a Low-Density Arc-Heated Wind Tunnel," NASA TN D-3829, 1967.

26. Shinn, J. L., Moss, J. N., and Simmonds, A. L. "Viscous Shock-Layer Heating Analysis for the Shuttle Windward Symmetry Plane with Surface Finite Catalytic Recombination Rates," In Progress in Astronautics and Aeronautics, Vol. 85, P. E. Bauer and H. E. Collicott, Eds. AIAA, NY, 1983.

27. Poll, D. I. A., "Boundary Layer Transition on the Windward Face of Space Shuttle During Re-Entry," AIAA Paper 85-0899, AIAA 20th Thermophysics Conference, Williamsburg, VA, June 19-21, 1985.

28. Schaaf, S. A., and Chambre, P. L. Flow of Rarefied Gases, Princeton University Press, Princeton, NJ, 1961.

29. Kogan, M. N., In Annual Review of Fluid Mechanics, Annual Reviews, Inc., Palo Alto, CA, 1973.

30. Bird, G. A. "Definition of Mean Free Path for Real Gases," Physics of Fluids, 26, Nov. 1983, 3222-3223.

31. Hurlbut, F. C. In Rarefied Gas Dynamics, Vol. I, (C. L. Brundin, Ed.), 5th Symposium, Academic Press, NY, 1967.

32. Nocilla, S. In Rarefied Gas Dynamics (J.Laurmann, Ed.), 3rd Symposium, Academic Press, NY, 1963.

33. Hurlbut, F. C. and Sherman, F. S. Physics or Fluids, 11, March 1968, pp. 486-496.

34. Butefisch, K. A. and Koppenwallner, G., in Rarefied Gas Dynamics,, Vol. 1, (R. Campargue, Ed.) 11th Symposium, CEA, Paris, 1979.

35. Freeman, Delma C., Powell, R. W., Naftel, J. C., and Wurster, K. E., "Definition of an Entry Research Vehicle," AIAA Paper 85-0969, AIAA 20th Thermophysics Conference, Williamsburg, VA, June 19-21, 1985.

36. Walberg, Gerald D., "A Survey of Aeroassisted Orbit Transfer," Jour. of Spacecraft and Rockets, 22, Jan. - Feb. 1985, pp. 3-18.

FOLDOUT FRAME

TABLE 1. Summary of measurements for improving heating rate an

Measurement	Apparatus/Technique	
On surface:		
Temperature	Thermocouples	Essentially sta
Pressure	Cap./Var. Reluctance Transducers	Essentially sta
Ht. Trans. Rate	Thermocouples/calorimeters	Essentially sta
Species Conc.	Mass spectrometer	Effusive inlet Problem of los: capture.
Off Surface Profiles:		
Local Velocity	Pitot tube rake	Intrudes into heating. Must velocity. Low
Density, T_t, T_r, T_v	Electron beam fluorescence (Refs. 8 and 12-14)	Quenching proc $300<T_t<1000K$.
Density, Velocity, T_t	Rayleigh scattering (Refs. 8 and 18-19)	Promising for t velocity and te $N>10^{15}/cc$.
Species Conc. (N, O, NO), T_r, T_v	Laser induced fluorescence (Refs. 8 and 15-17)	Need to evaluat particles. Res Could be more u get profiles.
Flow visualization photography:	Electron beam painting	Need to define
Boundary layer transition:	Pressure, heat transfer rate, temperature, acoustic sensors	Pressure fluctu film gauges on attachment line
Freestream properties:	Neutral/charged particle mass spectrometer, impact pressure probe.	See the SUMS sy subject to low I
Ion Density:	Electrostatic probe	Intrudes into b

for improving heating rate and local flow calculations

2 FOLDOUT FRAME

que	Comments
	Essentially state of the art devices required. STS heritage.
s	Essentially state of the art devices required. STS heritage.
	Essentially state of the art devices required. STS heritage.
	Effusive inlet flush with surface proposed. See Refs. (8-11). Problem of losing "true" samples of gas due to reactions after capture.
	Intrudes into boundary layer and will be subjected to high heating. Must be combined with density profile to yield velocity. Low Reynolds number effects, cf. Refs. 21-25.
. 8 and	Quenching process an obstacle at $N>10^{16}$/cc. Normally best at $300<T_t<1000K$.
18-19)	Promising for total density. More elaborate system needed for velocity and temperature. Velocity may be possible only when $N>10^{15}$/cc.
s. 8 and	Need to evaluate problems of shock heated gas and scattering from particles. Resolution of concentrations may not be very good. Could be more useful if reaction rates were better known. Can get profiles.
	Need to define operational evelope.
ate, rs	Pressure fluctuations, acoustic sensors below surface, and thin-film gauges on surface have been used in wind tunnels. Data on attachment line desirable.
ass e probe.	See the SUMS system described in Ref. 20. Impact pressure probe subject to low Reynolds number effect (see e.g. Refs. 21-25).
	Intrudes into boundary layer.

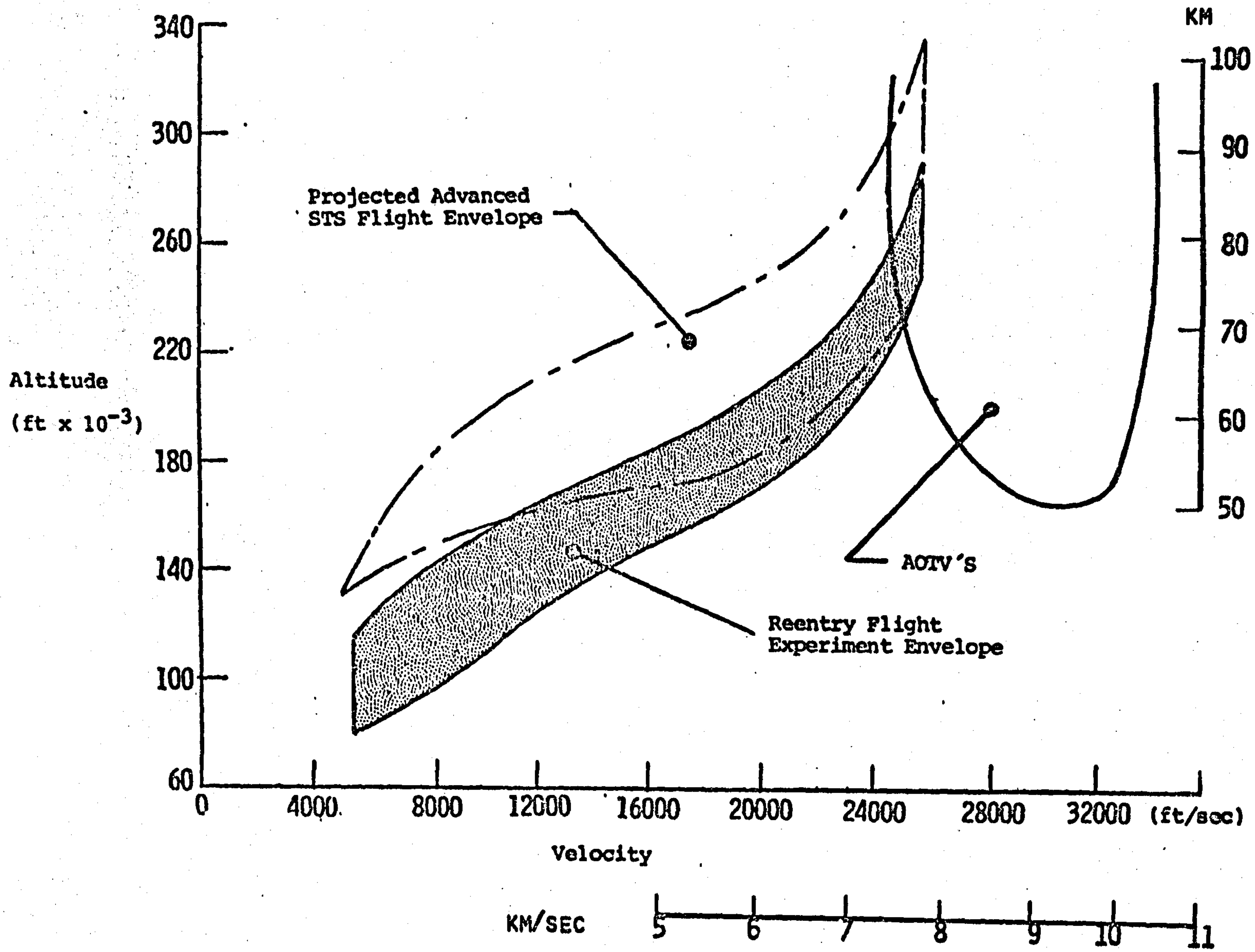

Figure 1. Altitude/Velocity Profiles of Reentry Flight

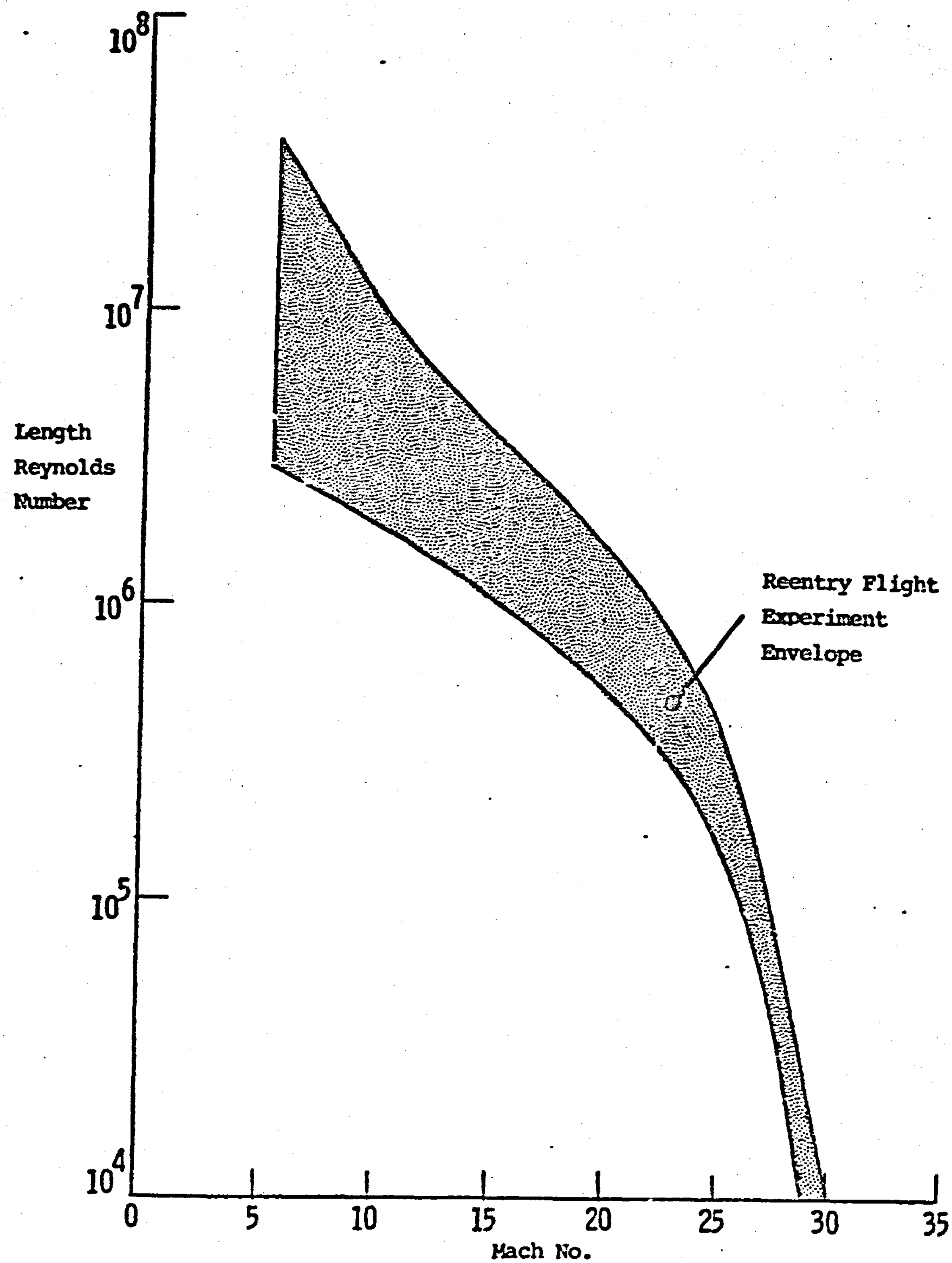

Figure 2. Flight Experiment Reynolds/Mach Profile

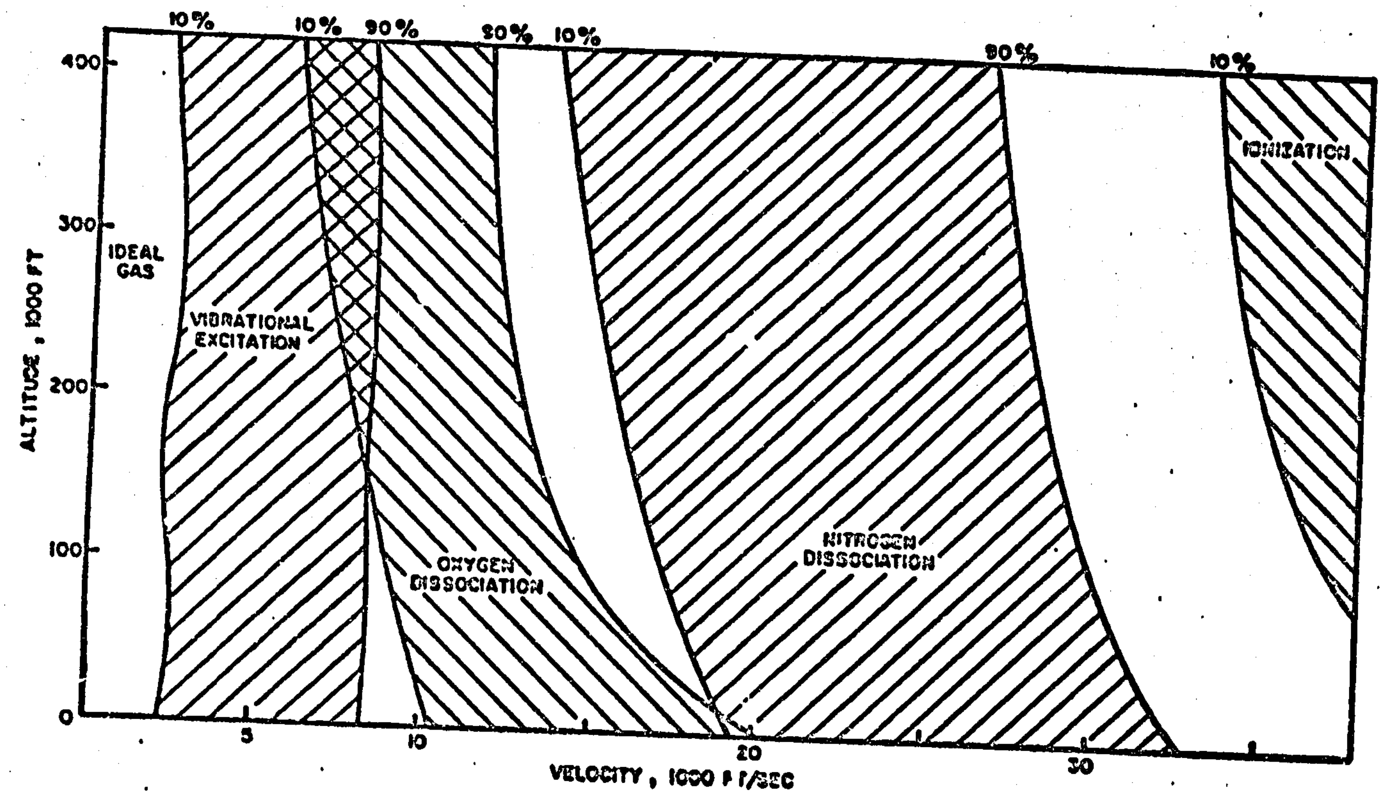

Figure 3. Energy Excitation Zones for the Stagnation Point

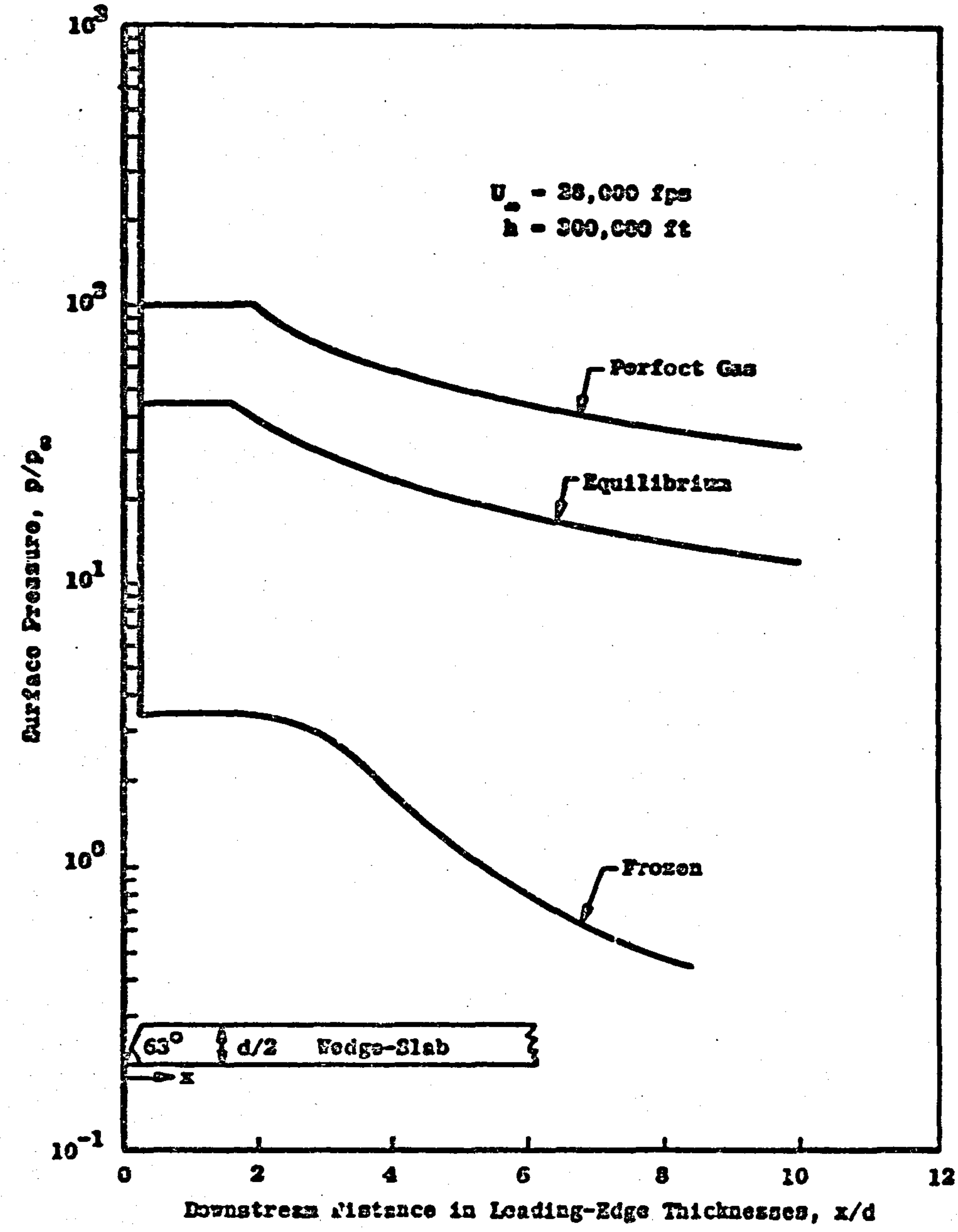

Figure 4. Example of Influence of Nonequilibrium Conditions on Pressure Distribution

(From Whalen, R.J., JAS, 29, Oct. 1962.)

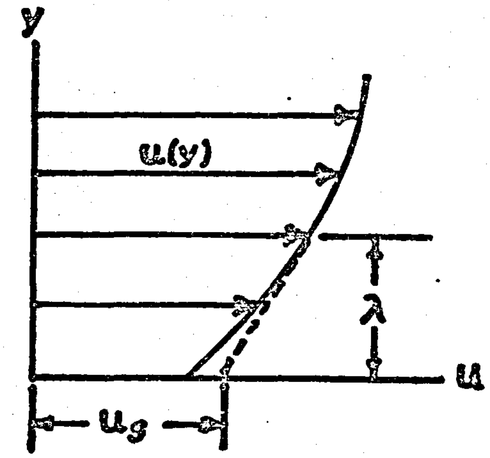

Figure 5. Slip Velocity

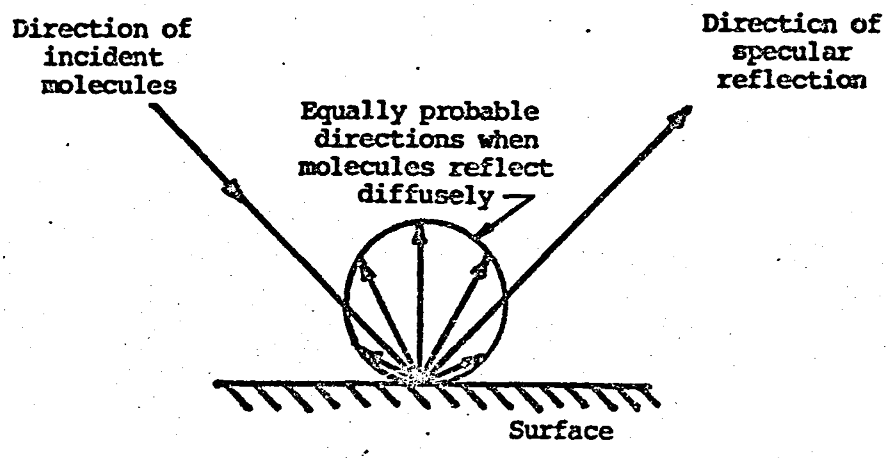

Figure 6. Gas-Surface Interactions

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